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How to Educate a Scientist

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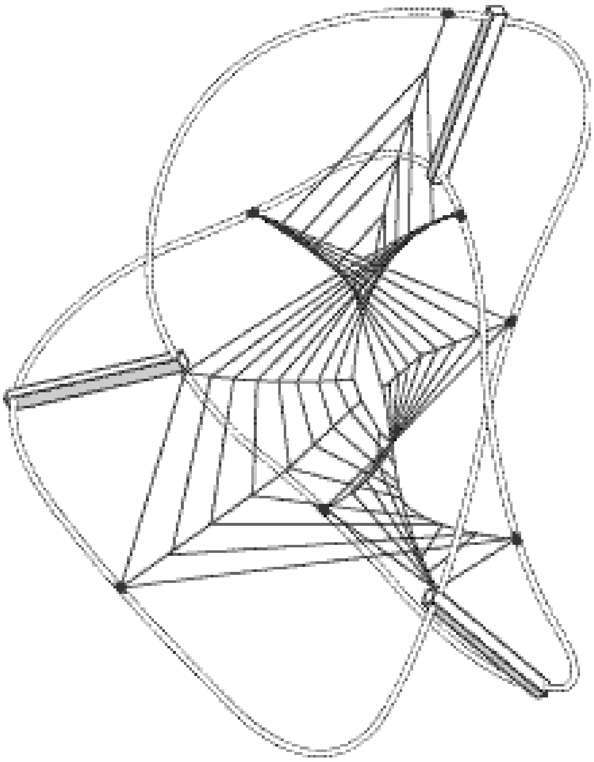

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How to Educate a Scientist

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How to Educate a Scientist.

A Paradox

Popular science is a multi-million pound publishing industry. Books purporting to divulge the secrets of the universe, of life, of time, of evolutionary psychology, of consciousness, of quantum theory, and of much else besides now fill large sections of bookshops in every major town and shopping centre in the country. Many of these books make it into the best-seller lists. They are widely and often respectfully reviewed, there are national prizes for them, and their authors become famous in their own right, with newspaper columns and radio and television appearances.

Whether the books do what they (or their publishers) claim they do is another question; and whether, if they do, they are understood by their readers (or even actually read beyond the first couple of chapters) is yet another question, and one not unrelated to our present topic, because if you lack a basic education in science, it is not clear that the deficit can satisfactorily be made up by a publisher's potboiler. So there is a question as to whether there really can be 'popular' science, that is, scientific understanding in the absence of harder and more systematic scientific study than can be found in popularly presented books. But the existence of a market for such things is a striking testament to the fact that people desire to know the things the books are about and what science can tell us about them. Science, or what science attempts to do, answers to a basic human need, as basic in its own different way as literature, music and the arts generally.

So why is it that in schools science is often so disliked by pupils? Why is it that many university science and maths departments have great difficulty filling their places at all, let alone with good applicants? Why is it that so few people seem to want to study science, compared to those who want to study business or English or the media?

It is over forty years since C.P.Snow gave his lecture on 'The Two Cultures', lamenting the widespread ignorance of science which Snow discerned among the general educated public. Full of cliché, the lecture has itself become a cliché, invoked every time the subject of science in education is raised. We all deplore what Snow deplored (ignorance of science). Since Snow there have been countless inquiries, initiatives, new methods, new curricula, to say nothing of endless speeches in parliament and newspaper editorials and professorial chairs in science education and the public understanding of science, all attempting to deal with the problem Snow pointed to. And all have failed. Science remains deeply unpopular in school and undersubscribed at university, and, as far as one can see in talking to undergraduates from subjects other than science, journalists, politicians, civil servants and the like, the level of general understanding of science no better than it ever was. That is the paradox: a thirst for scientific knowledge, together with a woeful inability to satisfy or even stimulate it among young people in school.

The Problem.

According to the House of Commons Select Committee on Science and Technology last year, school science is so outdated and boring that many young people are put off the subject for life. Actually the situation is rather worse than that. In hard science we are actually going backwards. A recent survey (see **The Times Educational Supplement**, 17/1/03) has shown that in 1980 50,447 candidates took A level physics; in 2000 the figure was 28,945. In maths the comparable figures were 83,508 and 60,734 respectively. From 1991-2 to 2000, there was a drop of 21% in A level physics entries, and in maths A level a drop in the same period of 8.5%. In fact, if one looks a little closer at the period in question, the really significant drops in both physics and maths entries started after 1989, when the GCSE, including the Double Science exam, had started to bite, a point to which we will return. Since 1988, A level science entries have dropped by 12%; over the last three years applications to university to study biology have fallen by 12%, and to study the physical sciences by 14%.

The survey from which the 1980 figures were extracted was actually about **girls** doing physics and maths. According to Professor Mary Smith, Dean of Applied Science at Lancaster University, science subjects have now been ‘demasculated’, but, she plaintively asks, ‘in demasculating them, have we actually made the total number of students drop?’ (In fact, despite ‘demasculisation’ the number of girls doing physics A level also dropped, from 9,727 in 1980 to 6,589 in 2000.) Even more revealing was the comment of the ‘teacher support manager’ in the Institute of Physics, who said that the Institute had not hitherto focused on the falling numbers of boys doing physics: ‘this is an interesting angle and not one that has been highlighted’.

So demasculisation clearly hasn’t worked, and one might wonder if obsession with gender and other ‘equality’ issues on the part of academic managers and curriculum planners has not actually contributed to the problem. Would they not have been better off simply making the subject in its proper rigour and challenge genuinely more available to larger numbers of pupils - or, failing that, devising ways of getting more genuinely qualified teachers?

Obviously both of these things would help. But we have to be careful here. In contrast to some of the noises coming out of government, the problem is not to make a subject like physics more ‘interesting’ or ‘relevant’ in some general sense. Not only is science extremely interesting as it is –for those prepared to learn. But science is not easy; and any ‘access’, if it is not a question of patronising pupils and the subject, must be a matter of finding ways of teaching hard material successfully. And science is not just hard; since Galileo at least it has also been formidably counter-intuitive, teaching us that the world is in fact, at a physical level, very different from how it appears, and also from how we

might think it was, in advance of scientific enlightenment. (This was, of course, part of what was involved in the transition from Aristotelian ways of conceptualising the physical world to those of modern science, on matters such as inertia and atomic structure, and part, too, of Descartes' philosophical programme: to convince people that we might have good reason to believe that the world is not as it appears, but as Galileo and other mathematical physicists demonstrate that it is, which is a conundrum with which philosophy of science still wrestles.)

So the real problem in science education is not that the material is not intrinsically interesting. It is fascinating. The problem is how to put over really hard and counter-intuitive stuff in a way which does not alienate the pupils or compromise the material. The real problem is how to make pupils competent enough to handle the hard material, because the real problem is not the intrinsic interest of the material, but the incompetence of pupils – and, as we shall see, teachers. And in this context, discussions about the morality of cloning or the politics of nuclear power or of Kyoto are just beside the point, an evasion of the real issue, and, in the absence of any real scientific understanding, a cruel deception played on pupils for the sake of apparent and transitory gains.

Apart from the content of what should be taught, the situation in physics teaching is little short of catastrophic.

Of people teaching physics in independent schools, some 79% are qualified in physics. But for the maintained sector, the figure is 32%. Of those in the state sector teaching GCSE physics, 66% do not have a relevant degree. 30% of them do not even have A level physics. In other words, nearly a third of those teaching GCSE physics in state schools have no qualification in the subject above the level at which they are supposed to be teaching. And if teacher training figures are anything to go by, the situation is not improving. Between 1993 and 2000 the number of physicists undertaking teacher training fell by 70% and the number of chemists by 30% (while biologists increased by 10%). And there is a similar problem with qualified maths teachers in schools, down on government figures from 40,500 in 1983 to 25,200 in 1997, and suspected by many to be as low as 20,000 currently, and still falling.

One might then say that the problem about physics in schools is largely to do with teaching (or more accurately with under or un-qualified teachers). To some extent the problem in state schools at GCSE is disguised by the fact that state schools generally take what is known as 'Double Science', that is to say an examination in all three physical sciences (Physics, Chemistry and Biology), which counts as two rather than three subjects in the GCSE count, but within which it is not easy to discern the level attained of the various components.

In fact, it is not the Double Award alone which is to blame, despite the way that in it and in the national curriculum the words 'Physics', 'Chemistry' and 'Biology' are replaced by confusing neologisms, such as 'Sc 4' and 'Materials and their Properties', presumably to make some point about the supposed artificiality of disciplinary boundaries (which is

not very helpful to the learner, or indeed the teacher, when the methods of physics and biology, say, are clearly very different).

But ideology and tinkering with names aside, physics, chemistry and biology are discernible in the Double Award and indeed in the National Curriculum. And some top independent schools, such as St Paul's Girls and North London Collegiate do enter their pupils exclusively for Double Science. The reasoning there seems to be that enough of each of the sciences is covered in Double Science to prepare pupils for A level – providing that each of the three disciplines is taught by a subject specialist, which in these cases it obviously is.

Where problems arise acutely is when a teacher from one science attempts to teach another, without sufficient qualifications or knowledge. To be blunt, as may be inferred from the figures already quoted, in many state schools physics and chemistry are being taught by biology teachers who may have little or no grounding in the other sciences, and quite possibly not much enthusiasm for them either. And even in the state sector the picture is by no means uniform. There are still 164 grammar schools and a number of good comprehensives and sixth form colleges where more traditional values and teaching may be expected. But there must be a very large number of state schools where pupils are just not being taught physics properly because the right teachers are not there to teach them. And a similar picture will also appear in maths, where there are also chronic shortages of well qualified teachers.

In its recent document on the future of 14-19 education, the government tells us that there are now 51% of pupils getting 5 grades A*-C at GCSE level, compared to 37% ten years ago. With good reason, some might think that this increase represents little more than rampant grade inflation, as we will see. But what the government does not tell us itself is that only 39% of 16 year olds get grade C or above in the three core subjects of maths, English and science, and that this figure goes down to 34.8% if we look only at pupils who went to non-selective secondary schools. In other words, in state comprehensives nearly two thirds of pupils fail to reach what is generally regarded as a basic pass in the core subjects, after 11 years of compulsory education, and this, of course, includes science. It would take us too far afield to discuss here the government's proposed solution to the problem of under-achievement at GCSE (basically, new and different exams which more can pass), but the figures for GCSE simply serve to underline the general poverty of achievement in maths and science at the age of 16. So it is hardly surprising that only comparatively small numbers want to go on with the subjects, and those that do come disproportionately from the independent and grammar schools.

And this would be so, even on the assumption that exams had not got easier. Apart from the very large increase in good grades over the past decade or so, there is plenty of anecdotal evidence that in maths and science at GCSE, along with other subjects, they have. Teachers will tell you that 'everyone knows that they have', while sometimes adding that this is not necessarily a bad thing. Indeed, it may not be, if unnecessary complications and irrelevant material have been eliminated, and even if some necessary material had gone, it might not matter so much if we were at least honest about what is

going on. Indeed when we seem inevitably to be drifting towards a six subject baccalaureate qualification for 18 year olds, honestly is particularly important. There may be arguments in favour of a qualification in six as opposed to three subjects (though, if there are, the benefits of such a system have to be set against the dis-benefits of preventing able and highly motivated 16 and 17 year olds from have the freedom to specialise in the things which enthuse them); but let us nor pretend that we could have a six subject qualification that did not erode content and difficulty, nor that such an erosion could take place without the need for a major re-consideration of what might be hoped for from senior school science.

But in the area of standards above all, we are, it seems, constitutionally incapable of public honesty. Ministers, officials and education experts go on parade each August when the results come out to assure the general public that standards have been maintained (and that anyone who dares to raise questions about standards is disparaging the 'achievements' of our young people – rather than criticising those who are deceiving them and the rest of us). And, against this optimistic view that only unnecessary complications have been cut out of the science curriculum, we have it on the authority of David Burghes, Professor of Mathematics in the Education Department at Exeter University 'that it has become obvious that a GCSE tells you nothing. You can get a grade C in mathematics without being able to do long division and multiplication or anything to do with decimal fractions without a calculator'.

Despite this and similar worries from teachers and academics who have looked into the matter, neither the government nor any of its agencies in prepared to investigate standards over time in public examinations, and in the late 1990s a proposal by the then Chief Inspector of Schools to undertake a thoroughgoing review of examination standards was quashed after his departure.

However, in recent years there have been some significant non-anecdotal indications that all is not well in school maths and science courses, and this goes right down to maths at primary school. Up to the age of 11, pupils do very little manipulative arithmetic (multiplying and dividing fractions, working out lowest common denominators, etc.) This leaves them unprepared for algebra at secondary school, and many actually get very little algebra. You can indeed get a grade B in maths GCSE with virtually no algebra. And weakness here has a significant impact on A level maths and science.

In 1995 the London Mathematical Society, along with the Royal Statistical Society and the Institute of Mathematics and its Applications, published a report entitled **Tackling the Mathematics Problem**. It was highly critical of the lack of essential technical facility on the part of entrants to university maths courses. They lacked analytical powers, and often had little understanding of what a mathematical proof was or of the need for precision in mathematics. It is noteworthy that during the 1990s at least 50 universities moved from three to four year courses in maths, presumably to compensate for the decline in knowledge of their incoming undergraduates.

In 1996 there was a report published jointly by SCAA and OFSTED on A level standards in maths, chemistry and English. Contrary to repeated statements by government ministers and officials to the contrary, this report did **not** say that there had been no decline in standards in the subjects concerned. On maths A level it commented unfavourably on the lack of algebraic content in the syllabus, and also on a huge increase on the permissible use of formula sheets in the exams. On chemistry it pointed out that between 1975 and 1995 there had been significant reductions in the content required, particularly on the detail of chemical reactions and in knowledge of fundamental chemistry, both organic and inorganic. And an internal inquiry by SCAA found that in A level physics there was virtually no calculus at all, partly no doubt as a response to weaknesses in mathematics at A level and lower down.

More recently an experienced GCSE level examiner, reported that in 1989 you needed to get 48% in the Oxford and Cambridge maths GCSE to get a grade C, whereas in 2000 it was a mere 18%. We also know that now 30% of candidates now get an A grade at A level. To reinforce this tale of woe, in 2000 the Engineering Council, in conjunction with the Institute of Mathematics and its Applications, the London Mathematical Society and the universities Learning and Teaching Support Network (for Maths, Stats and OR), published a report entitled **Measuring the Mathematics Problem**. In it, among other things, it reported that in a diagnostic test applied to a 1991 cohort at Coventry University the scores of those who got N (a fail) in A level maths in 1991 were virtually identical to those who got a grade C in 1997. And the continuation of the same study revealed that 1991's N-graders were equivalent to 1999's B-graders. In general, then, on certain basic mathemetical skills, A level standards in maths are dropping one grade every two years. And in a diagnostic test given at York University over 15 years, and reported separately in 2001, this finding is corroborated. A student with an A grade at A level now had a score on the test would have put him or her near the bottom of the cohort in 1986, and, even more striking perhaps, an average grade B student at A level was able to score only marginally better on the York test than could have been done by random guessing. (See K.L.Todd, 'A Historical Study of the Correlation between GCE Advanced Level Grades and the subsequent academic performance of well-qualified students in a University Engineering Department', **Mathematics Today**, Vol 37, No 5, 2001.)

The Engineering Council report also referred to the decline in students' concept of proof and understanding of algebra at GCSE, which it said 'undermined' A level mathematics 'at a stroke' in 'a key area from which it has not yet recovered'. It also pointed out that at A level there is a very diminished core (30% of the course) which, together with modularisation, has led to very different abilities in students coming to university even with A level maths. By contrast, the 1960s were a golden age, at least for A level maths. Regulated by the universities and the exam boards (and not as now by the government and its agencies – which is where some suspect many of our current problems originate), 'A level mathematics consisted mainly of Pure and Mechanics with the latter providing ample scope for the use and practice of algebra, trigonometry and calculus. With the benefit of hindsight this is now seen as a "golden age" for A level Mathematics in which able sixth formers, aiming for university, were inspired and stretched by a very talented teaching force.' (p 2)

What clearly seems to be a reduction of intellectual challenge in school examinations in science and maths cannot but have an effect on university work, and not just in terms of content. Pupils who have been poorly taught science in school will not know how to think scientifically or to solve problems in science. They will tend to rely on recipes they have been fed by their teachers, whose own grasp of scientific method may be shaky, as we have seen; pupils may come to believe that in science they could simply look up answers on the Internet, a phenomenon not unknown in subjects other than science, as all university teachers will testify. But reliance on recipes is particularly unfortunate in science, where not general learning or transferable ‘thinking skills’, but a certain particular sort of reasoning is of the essence. Undergraduates in science who have not been sufficiently challenged at school, and who have been given little sense of the intellectual struggle which science involves will be uncomfortable with the idea that in solving a problem they ought to go back to first principles and think things through from the start, in a mixture of empirical and analytical reasoning. They will lack just the sort of insight crucial to science. Crucially they will be unprepared for the demands of what ought to be a highly academic course of the sort that was offered in a fair number of universities not so long ago. And all this is reflected by the increasing provision in science courses of remedial courses and diagnostic testing, particularly in maths, and also by high failure and drop-out rates in some science programmes.

Obviously not all young people would be suitable for an academic course in physics, chemistry, biology or anything else, nor should they be expected to be, a point to which we will return. But some surely should be, even in the hard sciences, and there are worrying signs that in schools we are often not doing enough for the able, for those who could rise to the intellectual challenge of the subject, but who are not being given the opportunity. We cannot content ourselves with thinking that even if we are failing the great mass of pupils scientifically – which we surely are - we are still doing fine by the top. Many observers and university teachers believe that at school we are not doing fine by the top any more.

And there is also the massive problem of what the government calls access. Our leading universities are currently being cajoled, bribed and punished by the government into admitting more students from disadvantaged backgrounds. Fine, in principle. But how can a university run a top class degree in physics, say, if they have to take undergraduates from schools where there is no adequate provision in physics? How can very large differences in attainment level be reliably assessed in the selection process? How can ‘promise’ be detected in those who have been given no or very little feel for the subject at school or college? Foundation courses might be the answer, but who is going to provide them, and in the current dire shortage of science teachers, who is going to teach them? Nor can such courses cannot simply be bolted on to the first year of an existing course without fatally eroding the content and standards of that course.

The Remedy

One obvious reason why maths and the physical sciences are waning in our educational system is that they are hard. They also go against the spirit of the time in that in them there are right and wrong answers, better and worse solutions. That, though, is also their potential strength, and their challenge.

To illustrate the type of difficulty involved in science, let us take physics as an example. In dealing with a problem in physics, you have first of all to identify the phenomena under investigation. Then a conceptual model for the phenomena has to be elaborated. The model is then formulated in mathematical terms. Mathematical methods are then brought to bear to obtain a solution, and this solution then has to be re-interpreted in physical terms. None of these operations is easy, and even less easy is being able to move through the whole process, from physical reality through a model and its mathematical elaboration and application back to what one hopes is a better understanding of the physical reality. Many students find the interrelating of the maths to the physics particularly hard, and some, of course, are better at one part of the process than at the others. But clearly, someone who has mastered physics at a high level has acquired both knowledge and a whole battery of problem-solving skills, which is no doubt partly why good physics graduates are very much sought after not just in physics itself, but by employers in business and industry generally for roles where physics itself may not be needed.

It is, though, increasingly difficult to run high level degrees in physics, and in the light of our analysis of problem-solving in physics, the stripping out of mathematics from school physics and the superficial treatment of algebra and calculus in school maths syllabuses, to say nothing of poor teaching, all of which we have seen recently, must appear particularly unfortunate. Indeed the mechanics element of the old A level physics used to train students in precisely the kind of mathematical modelling and application crucial to physics at a serious level, but this is no longer the case. But there are other factors, as well, which militate against expertise in all the hard sciences.

These include the pressure on pupils – and schools – to maximise grades in public exams, and so a tendency for pupils to opt for subjects which are easier or, if that is thought to be offensive to media studies, business, sports studies and other increasingly popular options, for subjects which are perceived to be easier.

Then there are the connected factors of modularisation and over-assessment. Modularisation means that courses are split up into discrete chunks, which are assessed as and when taken. So far more of school time in the sixth form is spent on assessment and preparing for assessment than used to be the case, which is obviously a waste of teaching time. (Effectively most of the summer term in the first year of the sixth, now that pupils have to do AS levels, which are themselves examinations with a mechanistic,

unintellectual approach, closer to GCSE than to the old A level, as good pupils have themselves noticed and are beginning to complain about). But worse, perhaps, than wasted time, modularisation also means that it is far harder for pupils to get an overall view of their subject as a whole, and how what they learned at the start of a course relates to things they encountered later.

Finally there is the contemporary tendency in education, at university level as much as at school level, to characterise the enterprise in terms apply to training rather than to education. Notions like aims, objectives, learning outcomes and the like are simply not appropriate to education, which is about illumination in the very thing one is studying, an illumination which cannot be specified independently of what one is studying (hence no independently specifiable aims, etc). Learning an academic subject like physics or biology will also involve ingestion on the part of the learner of a whole raft of tacit knowledge of how the subject proceeds, and which, by definition, cannot be made explicit. In the case of scientific subjects this tacit knowledge will include things like a sense of the weight to be attached to specific pieces of evidence or a nose for a reasonable hypothesis in a given context and all the matters of judgement which come only with experience of working in a scientific team or laboratory.

If we want, as we surely should, to get to a situation in which physics and the other sciences can flourish at university level, we must first correct those tendencies in school education which militate against its possibility.

This means first having in schools sciences courses which will teach science and maths, without compromising their nature and their difficulties, to a sufficiently high level to prepare pupils for serious university work in these subjects. We must reverse the tendencies and both GCSE and A level to erode content and challenge. And in this context, it is surely not insignificant that the fall in A level uptake in physics and maths coincided with the introduction of the GCSE, an exam intended to be for 'all', and easier in approach than the more rigorously academic O level which preceded it.

So some of our current difficulties arise from an understandable, but misguided attempt to produce a common curriculum in the sciences for all, at least up to GCSE level. This has led to less pupils being less well-prepared for A level than previously, and has also had a knock-on effect on A level content. If A level has been eroded, at least part of the reason has to be that pupils are now embarking on A level courses with less knowledge and ability than was the case in earlier decades, even though the numbers of pupils is actually lower. So what is happening cannot even be defended in terms of access. It is a frightening thought that if A level science was as hard as it was 20 years ago, even less pupils than to-day's reduced numbers would be able to take it.

It is not, of course, the case that, globally speaking, we would need or expect very large numbers to be able or willing to take a science degree of high quality (though to remedy the desperate shortage of teachers in science in schools we need somewhat higher numbers than now). So we are not saying that a very high proportion of pupils in schools should be offered or encouraged to go into science courses of a higher level than the

current GCSE. But if A level is to be restored to its previous level, and if top universities are to be able to continue to offer seriously good degrees in science that do not require supplementation by Masters' courses, it is essential that some significant numbers of pupils, say 10%, be offered a higher level of science education from the age of 14 than is the case at present (and possibly be allowed to embark straight on the second year of degree courses, if much of the first year is involved in remedial or foundation work).

The question which this proposal immediately raises is whether a higher level science course for a smallish percentage of teenagers would be compatible with our other aim, of offering everyone some decent education in science. In principle there is absolutely no reason why not. Indeed, in some independent schools, such as St Paul's, something along these lines already happens. At the start of the GCSE course, boys are divided into those who will take Double Award science, and those who will take the three separate sciences at GCSE, obviously on the basis of observed scientific achievement and potential. If, after one year in the school (where boys enter at the age of 13), St Paul's feels able to make distinctions of this sort, there is absolutely no reason, egalitarian prejudice or laziness aside, why other schools should not make similar differentiations at that sort of stage. And given that the whole point of the differentiation is to give each category of pupil a scientific education tailored to their specific needs and aspirations, there is absolutely every reason why they should.

That is not to say that the GCSE and its counterpart the national curriculum, as it currently stands, would be suitable for all those not doing the accelerated science course, or indeed for any of them. As we have seen, the select committee obviously thinks it is not; and the government's advisors are proposing a new type of science curriculum which focuses far more on topical issues related to science, such as cloning, GM foods, pollution and global warming.

It is easy (all too easy) to see why politicians and those close to them might want school curricula which focused on topical and political questions, but that does not make it a good idea in science or in anything else. Actually the new proposals also say that there will be broad explanations of scientific theories such as to provide young people with 'a framework for making sense of the world'. It is hard to quarrel with that as an aim, but it is equally hard to resist the comment that physics, chemistry and biology already provide framework(s) for making sense of (parts of) the world, and the rider that if you want to know what these frameworks are and what they can tell us, and even make a reasoned estimation of their power and beauty and also of their limitations, there is absolutely no substitute for studying physics, chemistry and biology, as traditionally conceived. Focusing on contemporary issues raised by science before understanding the underlying scientific discipline on its own terms is likely to be limiting in itself, and also to distort understanding of the issues to boot. Doubtless those advocating a science curriculum which focuses on contemporary issues will say that this will not be at the expense of fundamental science, and it may not be. But our experience in the politics of educational reform suggests that one would be naïve in the extreme not to be worried that it might well be.

Making this point in favour of a notion of education as illumination (as opposed to education as a propaedeutic to political activism) does not, of course, say just what should be studied in physics, chemistry and biology, or how much. In a way the how much question is easier to answer. We could reasonably say that we want everyone still in compulsory education to be educated in science to the maximum extent possible for them, recognising in saying that, that this extent will vary considerably according to the ability (and motivation) of the pupil, and there may well be need more than one science stream for the 90% (or so) who are not going to specialise early in science. But it will also doubtless vary according to the competence of the teacher, the extent to which the teacher is prepared to challenge and extend the pupil, and also, crucially, according to the subject matter.

So, we are back with subject matter; but let us also return to our initial paradox. By a happy convergence those questions which form the subject matter of most books of popular science just are the central issues of the sciences: the nature of matter, cosmology, motion, time, force, energy, atomic structure, physical change, the nature of life, evolution and so on. This convergence is hardly surprising, for it is illumination in the most basic questions to do with the natural world which brings most people to science in the first place, either at school or later, and this is just what is provided by the fundamental theories and concepts in the various sciences.

Maybe school science has tended to concentrate too much on peripheral issues, on low-level observations and on what can be done in school laboratories, and not enough on fundamental questions. But this is probably a matter of degree, rather than of principle. In the national curriculum, as it currently stands, the fundamental issues just mentioned – and hence the basis for what might be called scientific literacy - are all present, which makes the extent of scientific illiteracy among our young people even more puzzling.

Conclusions

A whiff of honesty about where we are, and what we are trying to do in science education might get us a long way.

First, we are not trying to make everyone a scientist. Only a small proportion of the population is ever going to be a scientist in the sense that they do the subject professionally or even take a degree in it at a good university. But, for various reasons, partly to do with lack of teachers but also to do with unchallenging curricula and undemanding exams at school we are treating this section of the population badly. In schools, we are not educating scientists, or not educating them as well as we should be.

We should give up the pretence that all can follow the same syllabus and take the same exams right up to the age of 16, and differentiate both pupils and courses in science at the age of 14 or even earlier. Of course there will be some who are not chosen at 14, and who may show interest and potential later. But these are likely to be a minority, for whom conversion courses and summer schools could and should be provided at a later stage. But the important thing is not to hold back the high-achievers, on egalitarian grounds or

even on the grounds that some others will become high achievers later, because doing that is bad for to-day's high achievers and depresses standards all through the system. Nor should we force to-day's high achievers into some baccalaureate style course, where they are forced to do things they are not interested in, just because some employers and politicians think it is a good thing. If a bright 16 year old with a good set of GCSEs in a wide range of subjects is passionate about physics and can't stand foreign languages (his or her A* in French notwithstanding), why should he or she be forced to do foreign languages (or vice versa) just to satisfy some entirely factitious demand for 'breadth'? But if we insist on going down this road, let us at least be honest enough to admit that breadth and depth are often incompatible, and that breadth is all too often equivalent to mediocrity.

Secondly, we should define what level and type (or possibly levels and types) of scientific literacy we should seek to provide for those unlikely in the first instance to become professional scientists. We have argued here that scientific literacy should take as its focus the core theories and concepts of the sciences of physics, chemistry and biology, as far as this is possible for each level, because it is here that science provides the illumination all of us seek. In the promised re-drawing of the general science curriculum, while topical issues should not be excluded, neither should they displace or downgrade discussion of the scientific core.

Thirdly, as a corollary of points one and two, we should think seriously not just about special curricula for the scientifically able. In order to provide those curricula, we will also need specialist schools, in order to provide a critical mass of both pupils and staff. An intensive scientific education cannot realistically be provided for a just a handful of scientifically promising pupils in a school where there is in any case inadequate teaching in the subject. It is these pupils who are most of all let down by the present system, and as their situation will characteristically be found in areas of social disadvantage, it is a scandal from all points of view. The problem will be solved only by the (re-)invention of scientific grammar schools, particularly in the inner cities.

Fourthly, there should be an intensive campaign to recruit teachers, particularly in physics and maths. This may involve offering suitably qualified people better salaries than would be offered to teachers of English or history, say. And it may involve encouraging older qualified people from outside the teaching profession to come into schools on favourable terms. Both these suggestions will be bitterly resisted by those claiming to speak on behalf of the teaching profession, but if we do not do either or both these things, we will fail yet more pupils, particularly those from areas of disadvantage.

Fifthly, the teacher supply crisis is not going to be solved quickly. So we should explore other ways of encouraging interest in science in schools, maybe getting physics undergraduates from our top universities to go and teach specific topics in schools which need science input. And we should also lay on genuinely academic course of professional development to re-enthuse to-day's science teachers and even to attempt to make up their deficits in knowledge.

Sixthly we should re-examine the maths curriculum at all stages, including in the early ones. As things stand, it does not seem to be providing an adequate basis for science at any stage, which has a knock-on effect on the study of science. It may be that even for those who will not go on to specialise in science, our current approach to maths is insufficient, especially in algebra and what relates to algebra.

Finally, depressing as the situation may be, we do have an opportunity to improve matters. The government is talking about new curricula and also, more importantly, about greater differentiation of pupils especially after the age of 14. It talks a lot about specialist schools. It is also concerned to attract people into teaching in new and radical ways. And in response to the increasing worries about mathematics in November 2002 the government did set up and enquiry into post-14 mathematics. The government should be challenged to make good its rhetoric. It should widen its enquiry to science more generally, and be prepared to take radical and possibly unpopular steps, such as those canvassed here. The opportunity should be seized to confront and address our problems directly and honestly, in the interests both of science and of our young people.

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